

# ASCA AND RXTE OBSERVATIONS OF NON-THERMAL X-RAY EMISSION FROM GALACTIC SUPERNOVA REMNANTS: G156.2+5.7

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## ABSTRACT

We are conducting a survey of Galactic shell-type supernova remnants (SNRs) known or suspected to possess non-thermal components to their X-ray emission using new and archived observations made with such X-ray satellites as *ROSAT*, *ASCA*, *RXTE*, *Chandra* and *XMM – Newton*. This research is intended to probe the phenomenon of cosmic-ray acceleration by Galactic SNRs and estimate the maximum energy of cosmic-ray electrons accelerated by these sources. To illustrate this work, we examine the X-ray spectrum of the northwestern rim of an SNR suspected to have a non-thermal component to its X-ray emission, G156.2+5.7 (RX J04591+5147), over the energy range of  $\approx 0.7$ -12.0 keV using observations made by the *ASCA* GIS and the *RXTE* PCA. We compare fits made to the non-thermal component using two models, a simple power law and *SRCUT*. Both models give acceptable fits: the photon index derived from the fit made with the power law model ( $\Gamma = 2.0^{+0.2}_{-0.5}$ ) is comparable to values obtained for the bright rims of other SNRs with hard X-ray spectra. Using the *SRCUT* model, we derive a value of  $2.42^{+0.24}_{-0.23} \times 10^{17}$  Hz for the cutoff frequency  $\nu_{\text{cutoff}}$ : based on this value and assuming a mean magnetic field strength of 14  $\mu$ G, we estimate the cutoff energy  $E_{\text{cutoff}}$  of cosmic-ray electrons accelerated by G156.2+5.7 to be  $\approx 32$  TeV. This energy value is well short of the “knee” feature of the cosmic-ray spectrum.

## INTRODUCTION

In recent years the study of non-thermal X-ray emission from Galactic supernova remnants (SNRs) has attracted a considerable amount of interest within the astronomical community. Extensive research in this field commenced with the discovery that the X-ray emission from the Galactic SNR SN 1006 is predominately non-thermal (Koyama et al. 1995, Allen et al. 2001). Since this discovery, the number of Galactic SNRs which are known to possess spectra dominated by non-thermal X-ray emission has steadily increased and currently includes G347.3-0.5 (Koyama et al. 1997, Slane et al. 1999, Pannuti et al. 2003), G266.2-1.2 (Slane et al. 2001) and G28.6-0.1 (Bamba et al. 2001, Koyama et al. 2001) as well as SN 1006. Generally speaking, all of these Galactic SNRs are X-ray luminous, radio weak sources with shell-type morphologies expanding into low density ambient media. It is generally believed that the non-thermal X-ray emission is in fact synchrotron emission from electrons accelerated along the shock front of the SNR (e.g., Reynolds 1996, 1998; Reynolds and Keohane 1999), although others have argued that for at least some SNRs, the emission is instead produced by non-thermal bremsstrahlung (e.g. Vink and Laming 2002).

If the observed non-thermal emission does in fact have a synchrotron origin, it is possible to estimate the maximum energy of cosmic-ray electrons accelerated by these SNRs through an analysis of this emission. While it is currently believed that Galactic SNRs accelerate cosmic-ray particles to the well-known “knee” feature of the cosmic-ray spectrum ( $E_{\text{knee}} \approx 3000$  TeV), only a scant amount of data is available to test this hypothesis. To probe this issue in more detail, we are conducting an X-ray survey of a sample of Galactic SNRs using new and archived

Table 1. *ASCA* and *RXTE* Observations of the Northwestern Rim of G156.2+5.7 (RX J04591+5147)

Satellite and Instrument	SeqID or ObsID	Observation Date	R.A. (h m s) (J2000.0)	Decl. (° m s) (J2000.0)	Radius of Field of View (arcmin)	Effective Exposure Time (Seconds)	Range of Sampled Energies (keV)
<i>ASCA</i> GIS2+GIS3	50011000	1993 Sep 25	04 59 14	+52 29 56	22	32964	0.7–2.5
<i>ASCA</i> GIS2+GIS3	57059000	1999 Mar 5	04 55 36	+52 06 52	22	42570	0.7–2.5
<i>RXTE</i> PCA	50150-01	2002 Jan 25	04 56 45	+52 21 00	60	16160	3.0–12.0

observations made with such satellites as the *Röntgensatellit* (*ROSAT*), the Advanced Satellite for Cosmology and Astrophysics (*ASCA*), the Rossi X-ray Timing Explorer (*RXTE*), the X-ray Multiple Mirror Mission (*XMM-Newton*) and the *Chandra* X-ray Observatory. We are extracting emission spectra from the X-ray bright rims of Galactic SNRs known or suspected to possess non-thermal components to their X-ray emission. To illustrate this work, in this paper we consider one of the sources in our sample, G156.2+5.7 (RX J04591+5147): this SNR is suspected to possess both thermal and non-thermal components to its X-ray emission (Yamauchi et al. 1993, Yamauchi et al. 1999, Tomida 1999). We analyze observations made of the northwestern rim of this SNR using the Gas Imaging Spectrometer (GIS) aboard *ASCA* and the Proportional Counter Array (PCA) aboard *RXTE*. A detailed summary of these observations is provided in Table 1. In Figure 1, we present an X-ray image of G156.2+5.7 that was prepared using six pointed observations made with the Position Sensitive Proportional Counter (PSPC) aboard *ROSAT*.

## THE GALACTIC SNR G156.2+5.7 (RX J04591+5147)

The Galactic X-ray SNR G156.2+5.7 (RX J04591+5147) was discovered during the *ROSAT* All-Sky Survey and first described by Pfeffermann et al. (1991). Using a Sedov model to fit its X-ray spectrum, those authors derived an age of 26000 yr for G156.2+5.7, a distance of 3 kpc (which is supported by an independent distance estimate of 1–3 kpc based on the column density toward this source as well as HI observations) and an extremely low ambient density of  $0.01 \text{ cm}^{-3}$ . Assuming a distance of 3 kpc, the X-ray flux from this SNR given by Pfeffermann et al. (1991) ( $1.9 \times 10^{-10} \text{ ergs cm}^{-2} \text{ sec}^{-1}$  between 0.1 and 2.4 keV) indicates a luminosity of  $2.0 \times 10^{35} \text{ ergs sec}^{-1}$ , placing this source among the ten most luminous known Galactic X-ray SNRs. Complementary radio observations of G156.2+5.7 presented by Reich et al. (1992) indicated a modest flux density of  $4.2 \pm 0.1 \text{ Jy}$  at 1 GHz and an extremely low surface brightness of  $5.8 \times 10^{-20} \text{ ergs cm}^{-2} \text{ sr}^{-1}$ . Reich et al. (1992) also noted that the radio emission from the rims of this SNR is highly polarized, consistent with a synchrotron origin. These characteristics – high X-ray luminosity but low radio luminosity, low ambient medium density, and polarized radio emission from the rims of the SNR – are generally in common with the other Galactic SNRs known to possess X-ray spectra dominated by non-thermal emission. Additional X-ray observations of G156.2+5.7 have been presented using observations made with *ROSAT*, *Ginga* (Yamauchi et al. 1993) and *ASCA* (Yamauchi et al. 1999). Both of those papers commented on the harder component to the X-ray spectrum of this SNR, with Yamauchi et al. (1999) deriving a photon index of  $\Gamma = 2.1^{+0.3}_{-0.2}$  for a power-law fit to this component over the *ASCA* energy band. This index is comparable to the indices derived by power-law fits to the hard components of the *ASCA* X-ray spectra from other Galactic SNRs.

## OBSERVATIONS OF G156.2+5.7

### ASCA GIS2+GIS3 Observations

Both the GIS and the Solid-State Imaging Spectrometer (SIS) aboard *ASCA* (Tanaka et al. 1994) observed two different positions along the northwestern rim of G156.2+5.7, but because the GIS has a larger field of view than the SIS we only consider data from that instrument in this work. The GIS consists of two units (denoted as GIS2 and GIS3) of imaging gas scintillation proportional counters with a sealed-off gas cell equipped with an imaging phototube. The GIS is sensitive over the energy range of approximately 0.7 – 10 keV and has an energy resolution of  $\Delta E/E = 0.078$  at 6 keV (Ohashi et al. 1996, Makishima et al. 1996). The reduction process filtered data for elevation

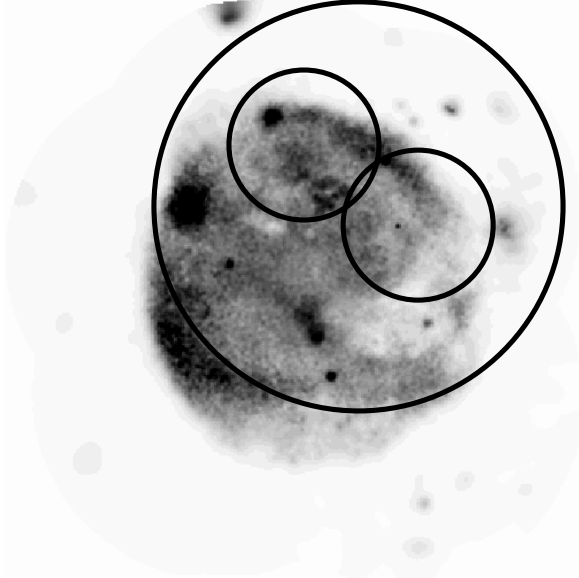


Fig. 1. *ROSAT* PSPC X-ray image of G156.2+5.7 depicting emission over the energy range of 0.4–2.0 keV (courtesy of Steven Snowden). The two small circles represent the fields of view of the *ASCA* GIS observations, while the large circle represents the field of view of the *RXTE* PCA observation (see Table 1 and “Observations of G156.2+5.7.”)

angle, stable pointing directions, the South Atlantic Anomaly and cut-off rigidity. The data were also screened for characteristics of the GIS internal background and screening based on event locations and rise time. The standard script “ASCASCREEN” was run to accomplish this reduction. To boost the signal-to-noise, for both pointings we combined the spectra observed by the GIS2 and GIS3 units and considered these combined spectra in our analysis.

### RXTE PCA Observations

Because of the rather large angular extent of G156.2+5.7 ( $\approx 110$  arcminutes, Green 2001), it was not possible to observe the entire SNR with a single pointing of the PCA, so we instead observed just the luminous northwestern rim. The PCA is a spectrophotometer comprised of an array of five coaligned proportional counter units that is sensitive to photons that have energies between approximately 2 and 60 keV. The energy resolution  $\Delta E/E$  of the array is 0.18 at 6 keV, and the maximum on-axis collecting area is about 6000 cm<sup>2</sup> at 9.72 keV. The PCA data were screened to remove the time intervals during which (1) one or more of the five proportional counter units is off, (2) G156.2+5.7 is less than 10° above the limb of the Earth, (3) the background model is not well-defined and (4) the pointing direction of the detectors is more than 0°.02 from the nominal pointing direction in either right ascension or declination.

### RESULTS

We first considered the two *ASCA* GIS observations of the northwestern rim: these observations were sensitive to thermal emission from G156.2+5.7 and we used the data from these observations to model this type of emission. We point out that the point source AX J0500+5238 lies along the northwestern rim and is believed to be a background galaxy unrelated to G156.2+5.7 (Tomida 1999, Yamauchi et al. 1999). We extracted spectra for two regions along this rim as sampled by the two *ASCA* GIS pointings (excluding flux from AX J0500+5238) and fit the spectra using a thermal *RAYMOND* model (Raymond and Smith 1977) with abundances frozen to solar values. Photoelectric absorption along the line of sight was fit using the *WABS* model, which is based on the Wisconsin cross-sections (Morrison and McCammon 1983) and relative elemental abundances as described by Anders and Ebihara (1982). For the spectra extracted from both regions we obtained acceptable fits using *WABS* × *RAYMOND* in both cases. In the case of the SeqID 50011000 observation, our fit values were  $kT = 0.48^{+0.19}_{-0.20}$  keV and  $N_H = 0.47^{+0.25}_{-0.19} \times 10^{22}$  cm<sup>-2</sup> with  $\chi^2/\text{degrees of freedom} = 42.6/149$ , while for the SeqID 57059000 observation our fit values were  $kT =$

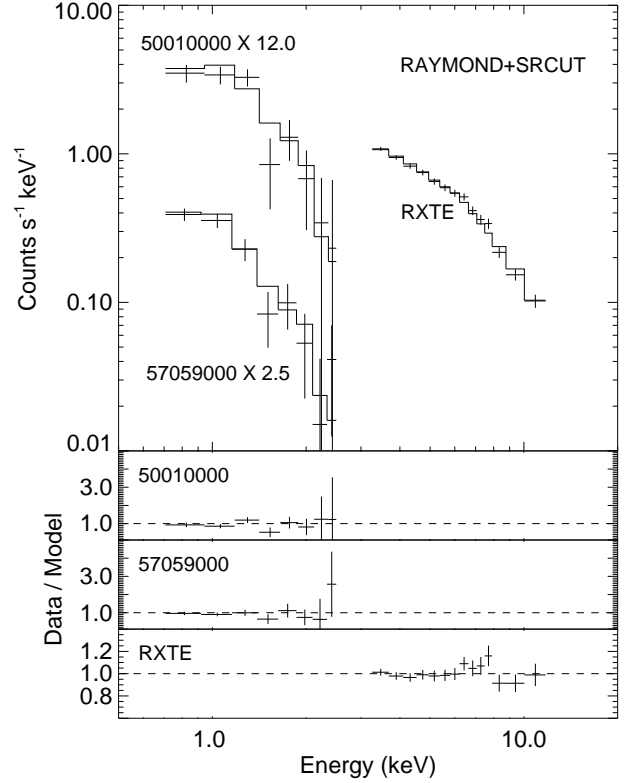


Fig. 2. X-ray spectra of the northwestern rim of G156.2+5.7 as observed by the *ASCA* GIS and the *RXTE* PCA (see Table 1 and “Results”).

$0.57^{+0.13}_{-0.17}$  keV and  $N_{\text{H}} = 0.24^{+0.15}_{-0.18} \times 10^{22} \text{ cm}^{-2}$  with  $\chi^2/\text{degrees of freedom} = 71.6/149$ . We therefore conclude that the thermal emission from the northwestern rim of G156.2+5.7. may be adequately modeled using the a column density and a temperature corresponding to the average values for these two parameters derived from these two fits; that is, assuming  $N_{\text{H}} = 0.36 \times 10^{22} \text{ cm}^{-2}$  and  $kT = 0.52$  keV.

We next considered the *RXTE* PCA observation of the northwestern rim of G156.2+5.7: because of the large field of view of the PCA, this observation sampled flux from G156.2+5.7 as well as AX J0500+5238 and a second background galaxy, 3C 130. To properly account for emission from these two galaxies, we first extracted and modeled a GIS spectrum for AX J0500+5238 and fit the spectrum over the energy range of 0.7–6.0 keV using a power law and the *WABS* model for photoelectric absorption. We obtained an acceptable fit ( $\chi^2/\text{degrees of freedom} = 90.5/448$ ) to the spectrum with a photon index  $\Gamma = 2.0^{+1.1}_{-0.7}$  and a column density  $N_{\text{H}} = 0.57^{+0.94}_{-0.57} \times 10^{22} \text{ cm}^{-2}$  (both broadly consistent with Tomida 1999 and Yamauchi et al. 1999). In the case of 3C 130 (which was not sampled by the *ASCA* GIS observations), Hardcastle (1998) obtained an acceptable fit to the spectrum of this source using the *RAYMOND* model ( $kT = 2.9^{+9}_{-2}$  keV) and a column density  $N_{\text{H}} = 0.9^{+0.5}_{-0.2} \times 10^{22} \text{ cm}^{-2}$ , assuming a redshift of 0.109. We adopt this model in our fitting procedure to describe the X-ray emission from 3C 130.

To model the non-thermal component to the observed X-ray emission from the northwestern rim of G156.2+5.7, we considered two different models: a simple power law model and the *SRCUT* model (Reynolds 1998, Reynolds and Keohane 1999). This latter model describes a synchrotron spectrum from a power-law distribution (with an exponential cutoff) of electrons in a uniform magnetic field. The photon spectrum is itself a power-law, rolling off more slowly than exponential in photon energies. The *SRCUT* model can be used to estimate the maximum energy of electrons accelerated by the SNR: we assume that the relativistic electron energy spectrum  $N_e(E)$  may be expressed as  $N_e(E) = K E^{-\Gamma} e^{-E/E_{\text{cutoff}}}$ , where  $K$  is a normalization constant derived from the observed flux density of the region of the SNR at 1 GHz,  $\Gamma$  is defined as  $2\alpha+1$  (where  $\alpha$  is the radio spectral index) and  $E_{\text{cutoff}}$  is the maximum energy of the accelerated cosmic-ray electrons. A crucial advantage of this model is that a resulting fit may be compared with two observable properties of an SNR, namely its flux density at 1 GHz and  $\alpha$ . Also, one of the fit parameters for this model is the cutoff frequency  $\nu_{\text{cutoff}}$  of the electron synchrotron spectrum, defined as the frequency at which the flux has dropped by a factor of 10 from a straight power law. This frequency may be expressed as

$$\nu_{\text{cutoff}} \approx 1.66 \times 10^{16} \left( \frac{B_{\mu\text{G}}}{10 \mu\text{G}} \right) \left( \frac{E_{\text{cutoff}}}{10 \text{ TeV}} \right)^2 \text{ Hz}, \quad (1)$$

where  $B_{\mu\text{G}}$  is the magnetic field strength of the SNR in  $\mu\text{G}$ , assuming the electrons are moving perpendicular to the magnetic field. By using the value for  $\nu_{\text{cutoff}}$  returned by *SRCUT*, an estimate for the maximum energy  $E_{\text{cutoff}}$  for the shock-accelerated electrons may be calculated.

We therefore modeled the *RXTE* PCA spectrum using a four component model: a component for the thermal emission from the rim, a component for the emission from AX J0500+5238, a component for the emission from 3C 130 and finally a component for the nonthermal emission from the rim. For the first three components, we adopt the previously-described models and parameter values, while for the final component we separately used and compared a power law model and an *SRCUT* model. Both of these models give acceptable fits to the non-thermal component of the spectrum: in the case of the power law model, for the photon index we obtain  $\Gamma = 2.0^{+0.2}_{-0.5}$  ( $\chi^2/\text{degrees of freedom} = 16.2/15 = 1.08$ ). Our value for the photon index is similar to values found for the bright rims of other SNRs that feature non-thermal spectra, such as G266.2–1.2 and G347.3–0.5 (Slane et al. 1999; 2001). This value is also comparable to the value obtained by Yamauchi et al. 1999 ( $\Gamma = 2.1$ ) in their analysis of *Ginga* observations of G156.2+5.7. Using the *SRCUT* model also yields an acceptable fit ( $\chi^2/\text{degrees of freedom} = 19.9/14 = 1.42$ ) with values of  $0.66 \pm 0.05$  and  $1.58^{+0.15}_{-0.14}$  Jy for  $\alpha$  and the normalization, respectively: both of these values are broadly consistent with the results of Reich et al. (1992). It is very remarkable that using the *SRCUT* model yields a fit which closely approximates the known radio properties of this SNR (note that the value for the normalization is almost half the total flux density at 1 GHz of G156.2+5.7 and reflects the bilateral radio morphology of this SNR). For the cutoff frequency parameter of this fit, we obtain  $\nu_{\text{cutoff}} = 2.41^{+0.22}_{-0.23} \times 10^{17} \text{ Hz}$ : assuming that the mean magnetic field strength of G156.2+5.7 is 14  $\mu\text{G}$  (Reich et al. 1992) and using Equation (1), we estimate that the maximum energy of cosmic-ray electrons accelerated along the northwestern rim of G156.2+5.7 is  $\approx 32$  TeV, well short of the “knee” feature of the cosmic-ray spectrum. In Figure 2, we present fits to the two *ASCA* GIS2+GIS3 spectra and the *RXTE* PCA spectrum that we have extracted for this analysis, using the *SRCUT* model to fit the non-thermal X-ray emission seen in the *RXTE* PCA spectrum. Additional X-ray observations of the northwestern rim of G156.2+5.7

Table 2. Gross Properties of Galactic SNRs with Non-Thermal-Dominated X-ray Spectra

SNR	SN 1006	G28.6–0.1	G156.2+5.7	G266.2–1.2	G347.3–0.5
Other Names	–	AX J1843.8–0352	RX J04591+5147	RX J0852.0–4622	RX J1713.7–3946
Distance (kpc)	2.2 <sup>1</sup>	7 <sup>2</sup>	1.3 <sup>3</sup>	1–2 <sup>4</sup>	6 <sup>5</sup>
Age (yr)	997 <sup>1</sup>	≤2700 <sup>2</sup>	15000 <sup>3</sup>	≈14000 <sup>†</sup>	≈8000 <sup>6</sup>
Size (arcmin)	30 <sup>7</sup>	13×9 <sup>7</sup>	110 <sup>7</sup>	120 <sup>7</sup>	65×55 <sup>7</sup>
$S_{1.4 \text{ GHz}}$ (Jy)	19 <sup>7</sup>	3(?) <sup>7</sup>	4.2±0.1 <sup>8</sup>	50(?) <sup>7</sup>	4±1 <sup>6</sup>
$\alpha$ ( $S_\nu \propto \nu^{-\alpha}$ )	0.6 <sup>7</sup>	–	0.5 <sup>7</sup>	0.3(?) <sup>7</sup>	≈0.55 <sup>9</sup>
$\Gamma$	2.1 <sup>10</sup>	2.1 <sup>2</sup>	2.1 <sup>3</sup>	2.6 <sup>4</sup>	2.4 <sup>5</sup>
$B$ ( $\mu\text{G}$ )	9 <sup>11</sup>	–	12–16 <sup>8</sup>	–	150( <sup>+250</sup> <sub>–80</sub> ) <sup>9</sup>
$n$ ( $\text{cm}^{-3}$ )	≈0.1 <sup>10</sup>	≤0.2 <sup>2</sup>	≈0.2 <sup>3</sup>	0.05 <sup>†</sup>	≈0.05–0.07 <sup>9</sup>
Progenitor Type	Ia <sup>1</sup>	–	–	II <sup>4</sup>	II <sup>5</sup>

References: <sup>1</sup> – Winkler et al. 2002, <sup>2</sup> – Bamba et al. 2001, <sup>3</sup> – Yamauchi et al. 1999, <sup>4</sup> – Slane et al. 2001, <sup>5</sup> – Slane et al. 1999, <sup>6</sup> – Ellison et al. 2001, <sup>7</sup> – Green 2001, <sup>8</sup> – Reich et al. 1992, <sup>9</sup> – Pannuti et al. 2003, <sup>10</sup> – Allen et al. 2001, <sup>11</sup> – Dyer et al. 2001. <sup>†</sup> – Calculated by Pannuti et al. 2003 using expressions derived by Slane et al. 2001 and assuming a distance of 1.5 kpc, a filling factor for a sphere of 1/4 and an explosion kinetic energy of 10<sup>51</sup> ergs.

with improved sensitivity are required to more rigorously constrain its spectral properties.

## COMPARISONS WITH OTHER GALACTIC SNRS

In Table 2, we present a comparison of the gross properties of five Galactic SNRs (SN 1006, G28.6–0.1, G266.2–1.2 and G347.3–0.5, as well as G156.2+5.7) with X-ray spectra which feature non-thermal emission. All of the SNRs in this class are X-ray luminous but radio faint and are expanding into regions of low ambient density ( $n \leq 0.2 \text{ cm}^{-3}$ ): it appears that searches for other SNRs in this class should concentrate on sources expanding into a low density media. However, we point out that two other SNRs which are known to possess non-thermal components to their X-ray spectra, Cas A and RCW 86, are expanding into high density ambient media. Therefore, the density of the ambient media is not the only factor in determining the strength of the non-thermal component to X-ray emission from SNRs. No clear evidence exists that any of these five SNRs are currently accelerating cosmic-ray electrons to the “knee” of the cosmic-ray spectrum: in fact, estimates for  $E_{\text{cutoff}}$  for each of these SNRs often fall short by an order of magnitude or more (Reynolds and Keohane 1999). Additional observations of Galactic SNRs using the present generation of X-ray observatories are required in order to analyze the phenomena of non-thermal X-ray emission and cosmic-ray acceleration by SNRs.

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## REFERENCES

- Allen, G. E., R. Petre and E. V. Gotthelf, X-ray synchrotron emission from 10–100 TeV cosmic-ray electrons in the supernova remnant SN 1006, *Astrophys. J.*, **558**, 739–752, 2001.
- Anders, E. and M. Ebihara, Solar-system abundances of the elements, *Geochimica et Cosmochimica Acta*, **46**, 2363–2380, 1982.
- Bamba, A., U. Masaru, K. Koyama, et al., A diffuse x-ray source, AX J1843.8–0352: Association with the radio complex G28.6–0.1 and identification of a new supernova remnant, *Publ. of the Astronomical Society of Japan*, **53**, L21–L24, 2001.
- Dyer, K. K., S. P. Reynolds, K. J. Borkowski, et al., Separating thermal and nonthermal x-rays in supernova remnants.

- I. Total fits to SN 1006 AD, *Astrophys. J.*, **551**, 439-453, 2001.
- Ellison, D. C., P. Slane and B. M. Gaensler, Broadband observations and modeling of the shell-type supernova remnant G347.3-0.5, *Astrophys. J.*, **563**, 191-201, 2001.
- Green, D. A., 2001, 'A catalogue of galactic supernova remnants (2001 December version)', Mullard Radio Astronomy Observatory, Cavendish Laboratory, Cambridge, United Kingdom (available on the World-Wide-Web at "<http://www.mrao.cam.ac.uk/surveys/snrs/>")
- Hardcastle, M. J., Jets, plumes and hotspots in the wide-angle tail source 3C 130, *Mon. Not. R. Astron. Soc.*, **298**, 569-576, 1998.
- Koyama, K., R. Petre, E. V. Gotthelf, et al., Evidence for shock acceleration of high-energy electrons in the supernova remnant SN 1006, *Nature*, **378**, 255, 1995.
- Koyama, K., K. Kinugasa, K. Matsuzaki, et al., Discovery of non-thermal x-rays from the northwest shell of the new SNR RX J1713.7-3946: The second SN 1006?, *Publ. of the Astronomical Society of Japan*, **49**, L7-L11, 1997.
- Koyama, K., M. Ueno, A. Bamba, et al., *Chandra observations of a new supernova remnant AX J1843.8-0352 / G28.6-0.1*, Proceedings of the Symposium "New Visions of the X-ray Universe in the XMM-Newton and Chandra era", Noordwijk, The Netherlands, 2001.
- Makishima, K., M. Tashiro, K. Ebisawa, et al., In-orbit performance of the gas imaging spectrometer onboard ASCA, *Publ. of the Astronomical Society of Japan*, **48**, 171-189, 1996.
- Morrison, R. and D. McCammon, Interstellar photoelectric absorption cross sections, 0.03-10 keV, *Astrophys. J.*, **270**, 119-122, 1983.
- Ohashi, T., K. Ebisawa, Y. Fukazawa, et al. The gas imaging spectrometer on board ASCA, *Publ. of the Astronomical Society of Japan*, **48**, 157-170, 1996.
- Pannuti, T. G., G. E. Allen, J. C. Houck, et al., *RXTE*, *ROSAT* and *ASCA* observations of G347.3-0.5 (RX J1713.7-3946): Probing cosmic-ray acceleration by a galactic shell-type supernova remnant, *Astrophys. J.*, in press, 2003.
- Pfeffermann, E., B. Aschenbach and P. Predehl, Discovery of a galactic supernova remnant with *ROSAT*, *Astron. Astroph.*, **246**, L28-L31, 1991.
- Raymond, J. C. and B. W. Smith, Soft X-ray spectrum of a hot plasma, *Astrophys. J. Supplement Series*, **35**, 419-439, 1977.
- Reich, W., E. Fürst and E. M. Arnal, Radio observations of the bright X-ray supernova remnant G156.2+5.7, *Astron. Astroph.*, **256**, 214-224, 1992.
- Reynolds, S. P., Synchrotron models for x-rays from the supernova remnant SN 1006, *Astrophys. J.*, **459**, L13-L16, 1996.
- Reynolds, S. P., Models of synchrotron x-rays from shell supernova remnants, *Astrophys. J.*, **493**, 375-396, 1998.
- Reynolds, S. P., and J. W. Keohane, Maximum energies of shock-accelerated electrons in young shell supernova remnants, *Astrophys. J.*, **525**, 368-374, 1999.
- Slane, P., B. M. Gaensler, T. M. Dame, et al., Nonthermal x-ray emission from the shell-type supernova remnant G347.3-0.5, *Astrophys. J.*, **525**, 357-367, 1999.
- Slane, P., J. P. Hughes, R. J. Edgar, et al., RX J0852.0-4622: Another non-thermal shell-type supernova remnant (G266.2-1.2), *Astrophys. J.*, **548**, 814-819, 2001.
- Tanaka, Y., H. Inoue and S. S. Holt, The x-ray astronomy satellite ASCA, *Publ. of the Astronomical Society of Japan*, **46**, L37-L41, 1994.
- Tomida, H., Synchrotron emission from the shell-like supernova remnants and the cosmic-ray origin, Ph.D Thesis, Kyoto University, 1999.
- Vink, J., and J. M. Laming, On the magnetic fields and particle acceleration in Cas A, *Astrophys. J.*, **584**, 758-769, 2003.
- Winkler, P. F., G. Gupta and K. S. Long, The SN 1006 remnant: Optical proper motions, deep imaging, distance and brightness at maximum, *Astrophys. J.*, **585**, 324- , 2003.
- Yamauchi, S., S. Ueno, K. Koyama, et al., X-ray spectrum and structure of the supernova remnant RX 04591+5147, *Publ. of the Astronomical Society of Japan*, **45**, 795-800, 1993.
- Yamauchi, S., K. Koyama, H. Tomida, et al. ASCA observations of the supernova remnant G156.2+5.7, *Publ. of the Astronomical Society of Japan*, **51**, 13-22, 1999.